Appendix F. Climate Change Trends and Projections for the Pacific Northwest

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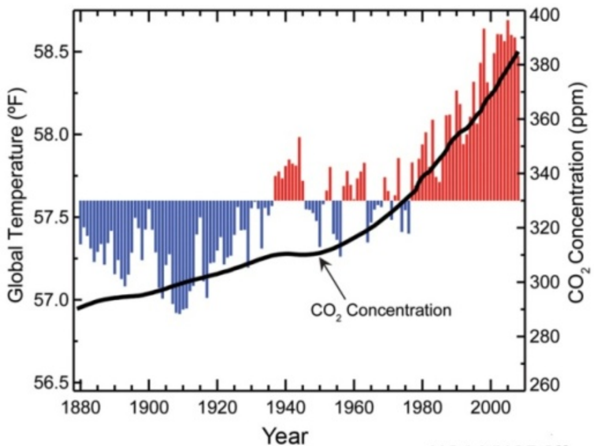
Changes in Temperature and Precipitation

There is a direct correlation between greenhouse gas (GHG) atmospheric concentrations and the temperature of the Earth's surface (IPCC 2007; Solomon et al. 2007; Figure 1, USGSRP, 2009; Huber and Knutti 2011). Global surface temperatures have increased about 1.5°F since the late nineteenth century to 2008 (USGCRP 2009), and the rate of temperature increase has risen threefold for the northern hemisphere in more recent years from 1979 to 2010 (Morice et al. 2012). By 2100, global temperatures are projected to rise another 2 to 11.5ºF (USGCRP 2009). The IPCC, a large group of scientists convened by the United Nations to evaluate the risk of climate change caused by human activities, reported in 2007 that "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (IPCC 2007).

Figure 1. Global Average Temperature and CO_2 Concentration from 1880 to 2008 (*Source:* USGSRP, 2009)



NOAA/NCDC[32]

Global annual average temperature (as measured over both land and oceans). Red bars indicate temperatures above and blue bars indicate temperatures below the average temperature for the period 1901-2000. The black line shows atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm). While there is a clear long-term global warming trend, each individual year does not show a temperature increase relative to the previous year, and some years show greater changes than others.[33] These year-to-year fluctuations in temperature are due to natural processes, such as the effects of El Niños, La Niñas, and the eruption of large volcanoes.

Average Northern Hemisphere temperatures during the second half of the 20th century were very likely higher than during any other 50-year period in the last 500 years and likely the highest in at least the past 1300 years (IPCC 2007, p10, Physical Science Summary for Policy Makers, Contribution of Working Group I). Globally, nine years in the first decade of the 21st century (2001 to 2010) rank among the ten warmest years in the 130-year instrumental record (1880 to present) (NCDC 2010; see Table 1). The new 2010 record is particularly noteworthy because it occurred in the presence of a La Niña (a period of unusually cold ocean temperatures in the Equatorial Pacific) and a period of low solar activity, two factors that have a cooling influence on the planet. However, in general, decadal trends are far more important than any particular year's ranking. The 2001-2010 decade was the warmest since the start of modern measurements in 1850 and continued an extended period of pronounced global warming. More national temperature records were reported broken than in any previous decade. (WMO 2013)

Donat and Alexander (2012) find that globally, both daytime and nighttime daily maximum and minimum temperatures have shifted significantly from 1951–1980 to 1981–2010. Changes are greater for daily minimum (night-time) temperatures than for daily maximum (daytime) temperatures. The authors also conclude that the distribution of global daily temperatures has become "more extreme" since the middle of the 20th century.

Karl et al. (2012) find that in the contiguous U.S., the warmth of the spring and summer of 2011 and 2012 is unprecedented in the observational record for its overall magnitude, spatial extent, and persistence and is part of a highly significant national trend. In the absence of trends, the standardized temperature anomaly for spring and summer of 2012 was about a one in 1600-year event for maximum temperature and 450-year for minimum temperature. The all-time largest fraction of the nation-setting record monthly maximum temperature occurred during March 2012 (37.2% of the United States), and July 2012 recorded the highest monthly mean ever recorded. But, summer months of other years had more extensive areas of record- breaking monthly mean maximum temperature (in May 1934 and June 1936, 20% of the nation experience record-setting maximum temperature).

Table 1. Top 10 Warmest Years in the Instrumental Record from 1880 to 2010 (*Source:* NCDC, 2010). The *instrumental record* refers to the period with recorded temperatures. Anomalies are differences from the mean.

Global Top 10 Warmest Years (January-December)	Anomaly (˚F)
2010	1.12
2005	1.12
1998	1.08
2003	1.04
2002	1.04
2009	1.01
2006	1.01
2007	0.99
2004	0.97
2001	0.94

Trends in global precipitation are more difficult to detect than changes in temperature because precipitation is generally more variable and subject to local topography. However, while there is not an overall trend in precipitation for the globe, significant changes at regional scales can be found. A new study of the ocean's changing salinity confirms that water-cycle amplification has occurred for the past half-century (based on findings from ocean water sampling from 1950-2000) and shows that wet places are getting wetter (e.g., Pacific Northwest) and drier places getting drier (e.g., South Pacific) (Durack et al., 2012). This study concluded that the water cycle had sped up roughly 4% while the surface warmed 0.5°C in the past 50 years (warm air can hold more water vapor thus accelerating the water cycle).

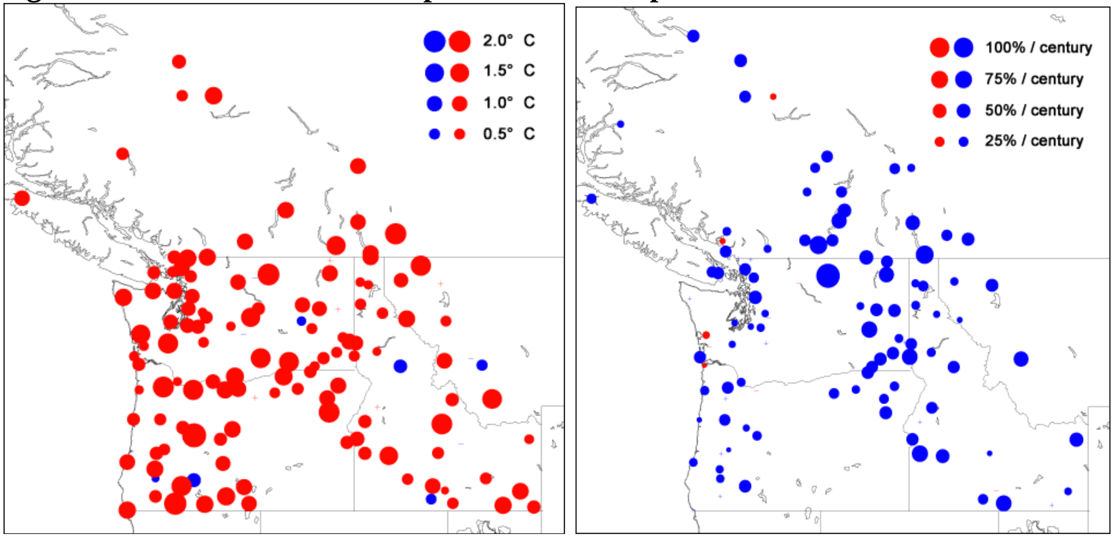
Just as important as precipitation totals are changes in the intensity, frequency, and type of precipitation. Warmer climates, owing to increased water vapor, lead to more intense precipitation events, including more snowstorms and possibly more flooding, even with no change in total precipitation (Dominguez et al., 2012). The frequency of extreme single-day precipitation events has increased, especially in the last two decades. Paradoxically more droughts and heat waves have occurred because of hotter, longer-lasting high pressure systems.

Pacific Northwest Climate Change Indicators and Trends

Temperature and Precipitation: In the Pacific Northwest, regionally averaged temperature rose 1.5°F between 1920 and 2000 (Figure 2, CIG), slightly more than the global average. Warming was largest for the winter months of January through March. Minimum daily temperatures have increased faster than maximum daily temperatures. Longer-term precipitation trends in the Pacific Northwest are more variable and vary with the period of record analyzed (Mote et al. 2005). Looking at the period 1920 to 2000, precipitation has increased almost everywhere in the region. Most of that increase occurred during the first part of the record.

In the Pacific Northwest, increased greenhouse gases and associated warmer temperatures have resulted in a number of physical and chemical impacts to the region. These include changes in snowpack, streamflow timing and volume, flooding and landslides, sea levels, ocean temperatures and acidity, and increased disturbance regimes such as wildfires, insect, and disease outbreaks (USGCRP 2009).

Figure 2. Trends in Annual Temperature or Precipitation from 1920 to 2000



Source: Climate Impacts Group (http://cses.washington.edu/cig/pnwc/pnwc.shtml#pastfuture).
Left panel: Red (blue) circles indicate warming (cooling) air temperatures. right panel: Red (blue) circles indicate or decreasing (increasing) precipitation.

Historical Trends at Winthrop, Washington: For trends local to the Hatchery we turn to the United States Historical Climatology Network (USHCN) which provides a high-quality data set of daily and monthly records of basic meteorological variables from 1,218 observing stations throughout the continental U.S. (Menne et al. 2009; 2010) The data have been corrected to remove biases or heterogeneities from non-climatic effects such as urbanization or other landscape changes, a possible movement of a meteorological station, and instrument and time of observation changes. A USHCN station is located at Winthrop, Washington, and the most recent 30-year trends are provided in the tables and figures below. The average yearly temperature change has increased 1.14^0F over the past 30 years and precipitation has decreased 1.8% (Figures 5, 6). More striking are the seasonal trends (Table 2) which show warmer seasonal average temperatures of $+1.98^0$F winter, $+1.41^0$F summer, and $+1.41^0$F fall; and cooler springs (-0.27^0F). Minimum temperatures are rising faster than mean and maximum temperatures: $+2.46^0$F Winter;

+0.92^{0}F Spring; +2.21^{0}F Summer; and +2.52^{0}F Fall. The region has experienced drier summers (-18.4% in precipitation), Springs (-18.3%) and Falls (-7%), although it should be noted that Summer seasons are naturally low in precipitation thus large percentage reductions result from relatively small precipitation changes.

Table 2. Annual and Seasonal 1981-2010 Trends in Water Year Total Precipitation and Temperature for Hermiston, Oregon (USHCN Data)

	Annual	Winter (Dec-Feb)	Spring (March-May)	Summer (June-Aug)	Fall (Sept-Nov)
Precipation	-1.8%	+7.7%	-10.7%	-18.3%	-7%
Mean Temperature	+1.14^{0}F	+1.98^{0}F	-0.27^{0}F	+1.41^{0}F	+1.66^{0}F
Maximum Temperature	+0.28^{0}F	+1.52^{0}F	-1.44^{0}F	+0.66^{0}F	+0.8^{0}F
Minimum Temperature	+2.03^{0}F	+2.46^{0}F	+0.92^{0}F	+2.21^{0}F	+2.52^{0}F

These changes are somewhat greater than the average for the Pacific Northwest (as shown in Mote et al. 2005). Winter and Spring temperatures, particularly in January and March, have been shown by other studies to be increasing significantly across the West (Hamlet and Lettenmaier 2007; Knowles et al. 2006). Such increases are important; warmer winters can cause more precipitation to fall as rain versus snow, resulting in reduced spring snowpack, earlier snowmelt, and changes in streamflow (Stewart et al. 2005; Arismendi et al. 2013a; Safeeq et al. 2013). Warmer summers can lead to increased fire frequency and drought, longer growing seasons, and increased water requirements (USGCRP 2009).

Figure 5. Trend in Water Year Average Temperature for Winthrop, Washington, from 1925 to 2010 (USHCN Data)

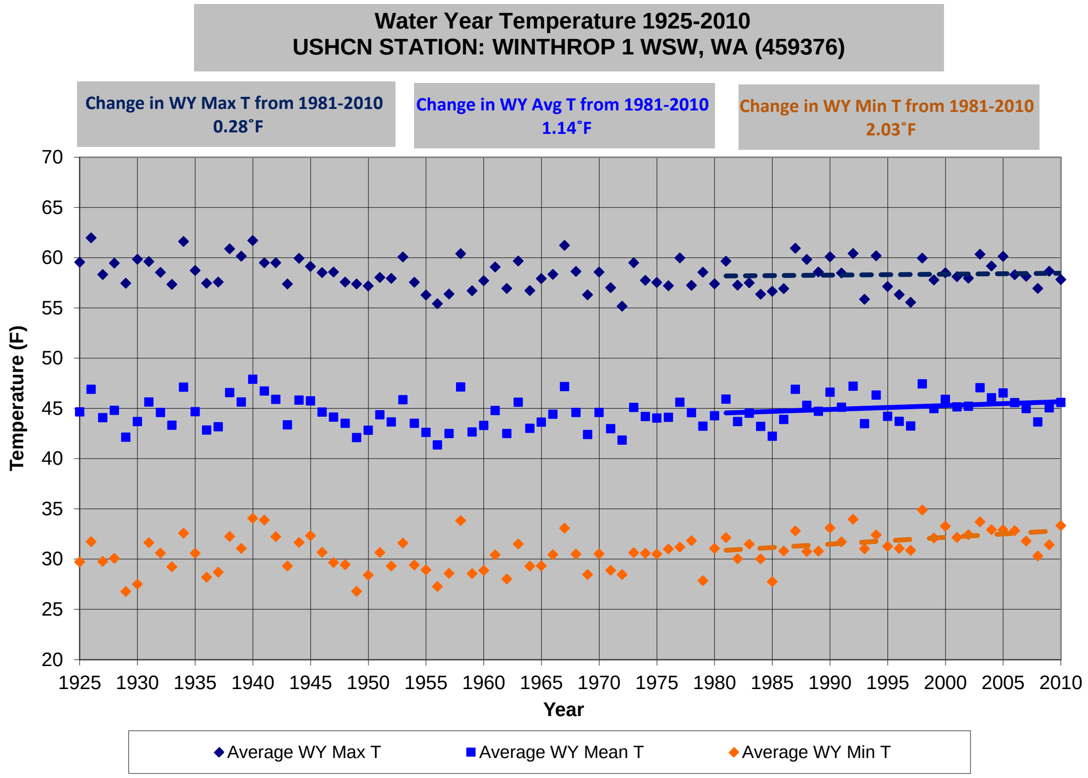
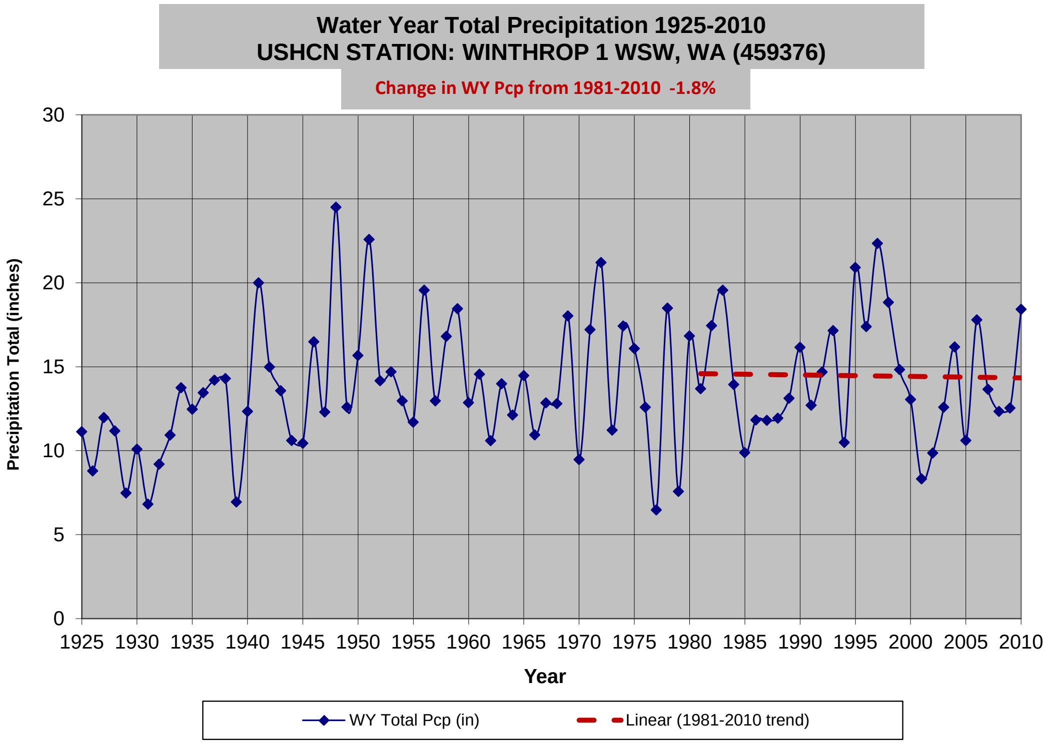


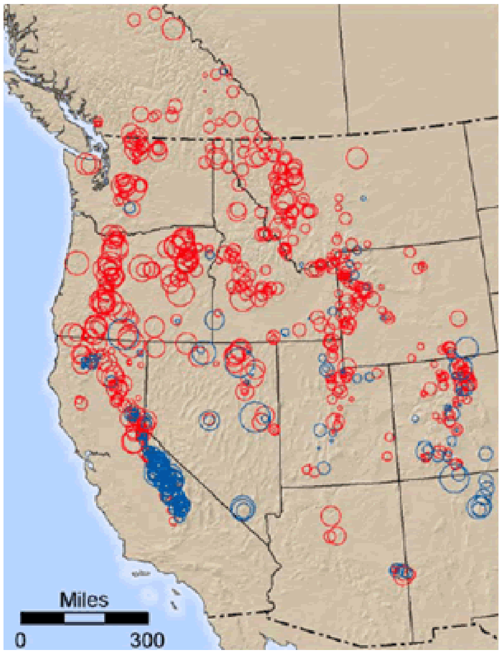
Figure 6. Trend in Water Year Total Precipitation for Hermiston, Oregon from 1925 to 2010 (USHCN Data)



Snowpack Changes: One of the most pronounced responses to warmer winter temperatures in the Pacific Northwest has been the loss of spring snowpack (Mote et al. 2005; Casola et al. 2007; Pederson et al. 2013; Sproles et al. 2013). As temperatures rise, the likelihood of winter precipitation falling as rain rather than snow increases. This is especially true in the Pacific Northwest where a significant amount of mountainous areas with snow accumulation are at relatively low elevation and winter temperatures are near freezing (Nolin and Daly 2006). Small increases in average winter temperatures can lead to increased rains, reduced snowpack, and earlier snowmelt. The loss of spring snowpack in the Pacific Northwest has been significant, with most of the weather stations showing a decrease on average (Figure 3). Data recorded each April 1 show that snowpacks have declined 25 percent over the past 40 to 70 years (Figure 3, Mote et al. 2005). The fact that the declines are greatest at low-elevation sites and that the trend has occurred in the absence of significant decreases in winter precipitation implicates temperatures rather than precipitation as the cause of the trend.

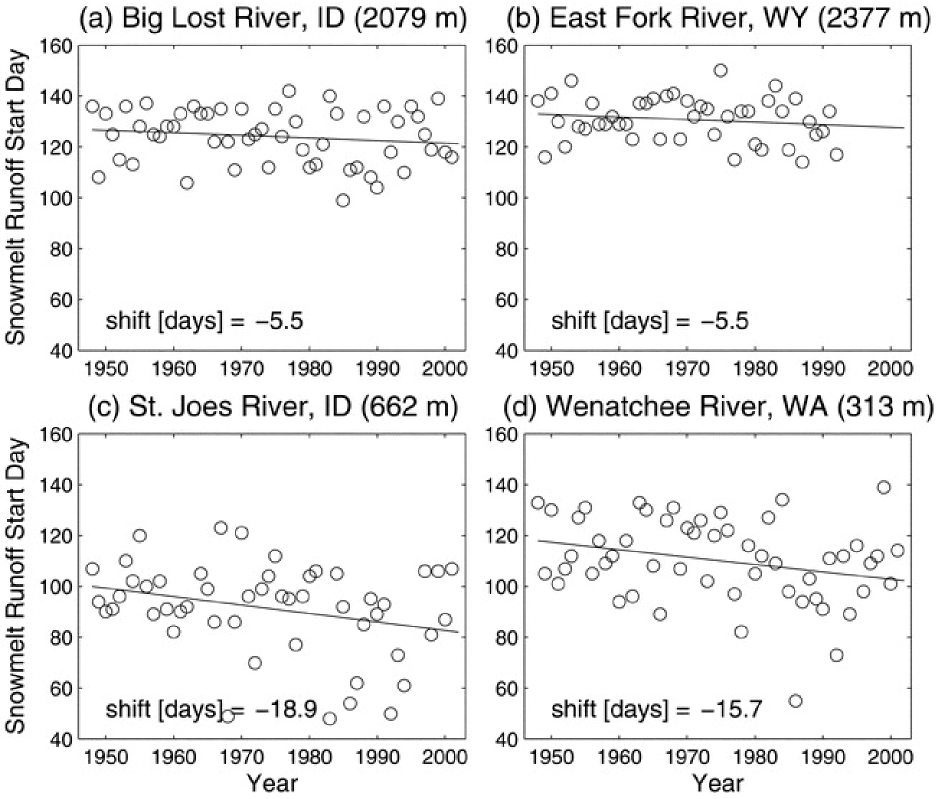
Pederson et al. (2013) find that after 1980, snow cover at low to middle elevations in the Rocky Mountains has dropped by approximately 20%, partly explaining earlier and reduced streamflow, and both longer and more active fire seasons. The study finds that this is predominately due to warmer springs (Feb-March) and fins that the post-1980 period is a “turning point” where temperature influences snowpack accumulation more than precipitation for large-scale snowpack patterns. (The past millennium’s snowpack before 1980 tracked regional precipitation climate variability, for example those caused by the El Nino Southern Oscillation and Pacific Decadal Oscillation.)

Figure 3. Trends in April 1 Snow Water Equivalent in the Western United States from 1950 to 1997 (*Source:* Mote et al. 2005)
Red (blue) circles indicate decreasing (increasing) snow water equivalent, with the size of the symbol indicating the magnitude of the trend



Streamflow Changes: The decrease in spring snowpack and earlier snowmelt has led to a change in streamflow in many systems, including earlier spring runoff peaks, increased winter streamflow, and reduced summer and fall streamflows when water temperatures are at their highest (Stewart et al. 2005; Arismendi et al. 2013a; Safeeq et al. 2013). Rain-dominated systems and systems with higher groundwater base flow are less sensitive. Stewart et al. (2005) for example, examined 302 streamflow gages in the western United States and reported that the timing of winter runoff and annual streamflow had advanced by one to four weeks from 1948 to 2002. The degree of change depends on the location and elevation of the specific river basin. Basins located significantly above freezing levels have been much less affected by warmer temperatures than those located at lower elevations (Figure 4). River basins whose average winter temperatures are close to freezing are the most sensitive to climate change, as is apparent from the dramatic shifts in streamflow timing that have resulted from relatively small increases in wintertime temperatures. The advance in streamflow timing also results in decreased summer and fall base flows, at precisely the time when streamflow is needed most. In addition, warmer temperatures have lengthened the growing season (defined as the time between the last frost of spring and the first frost of fall) in the western United States by an average of about 10 to 15 days. Warmer temperatures and longer growing seasons increase water requirements for evapotranspiration, hydropower, and irrigation, resulting in potential water supply shortages and conflicts.

Figure 4. Observed Spring Pulse of Snowmelt-generated Streamflow for Two High (a and b) and Two Mid-elevation (c and d) Pacific Northwest Streams, Illustrating the Much Greater Advance in Timing in the Mid-elevation Streams (from Stewart et al., 2005)



Stream Temperatures: A number of landscape factors and stream characteristics influence stream temperatures such as the amount of solar radiation streams receive; evaporation rates; bed conduction; friction of the water with the bed and the banks; air temperature; valley and channel morphology such as channel slope and orientation, and features such as pools, riffles and rock steps; amount of groundwater and/or hyporheic flows; the presence of human modifications such as impoundments; and other factors (Webb et al. 2008). In a study of the landscape, stream, and channel factors that control summer stream temperatures in unregulated Pacific Northwest streams, Mayer (2012) finds that baseflow index (groundwater influence in a stream) and stream channel slope best explained summer stream temperatures and thermal sensitivities regionally.

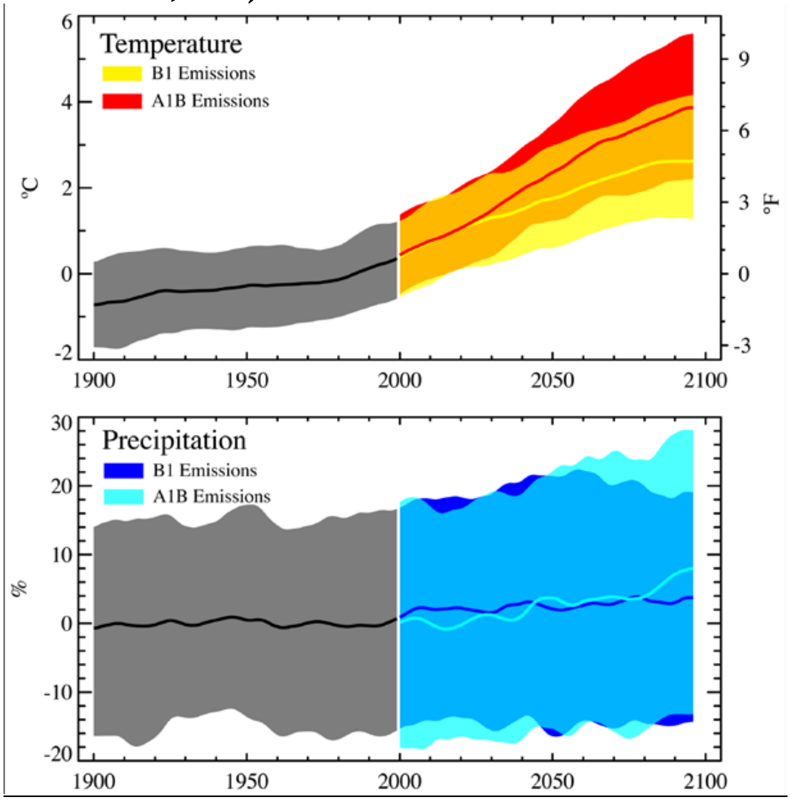
Research in the Pacific Northwest by Isaak et al (2011) on unregulated streams found statistically significant increasing stream temperature trends with rates of warming highest during the summer (raw trend, +0.17°C/decade; reconstructed trend, +0.22°C/decade). Air temperature increases were found to be the dominant factor explaining long-term stream temperature trends (82–94% of trends) and inter-annual variability (48–86% of variability), except during the summer when discharge accounted for approximately half (52%) of the inter-annual variation in stream temperatures.

Aresmendi et al. (2012) found that not all streams in the Pacific Northwest exhibit warming trends depending on the time scale, suggesting possible local variation and other factors at play. This study recommends more long-term data on minimally impacted streams is needed throughout the region. Following up, five long-term gage stations (>30-years) from western Oregon were analyzed by Aresmendi et al. (2013b) and key findings include: warming of sites in both winter and summer, with the greatest trends in the winter; during the summer, although both increased, daily minimum temperatures increased more than daily maximum values; and duration and frequency of cold events are declining, whereas warm events are more frequent and longer in duration than cold events. Research from long-term temperature monitoring sites in Europe also show strong evidence of warming stream temperatures correlated to rising air temperatures and climate cycles (e.g., Pacific decadal oscillation) with deviations associated with landscape factors and stream characteristics as described above (Webb and Nobilis 2007; Hari et al. 2006).

Future Climate Change

Looking toward the future, the University of Washington Climate Impacts Group (CIG) has projected changes in mean annual temperature and precipitation for the Pacific Northwest, based on several global climate models and two carbon emissions scenarios (Mote and Salathé 2009, 2010 as shown in Figure 7; Littell et al. 2009). Considering both scenarios, average annual temperature is projected to increase 2.0°F by the decade of the 2020s, 3.2°F by the decade of the 2040s, and 5.3°F by the decade of the 2080s, relative to the 1970-1999 average temperature. The projected changes in average annual temperature are substantially greater than the 1.5°F (0.8°C) increase in average annual temperature observed in the Pacific Northwest during the twentieth century. Seasonally, summer temperatures are projected to increase the most. It should be noted that actual global emissions of greenhouse gases in the past decade have so far exceeded even the highest emissions scenario (the A2 scenario), which was not modeled by CIG. If this trend continues, the temperature increases could actually turn out to be much greater than those projected in Figure 7.

Figure 7. Simulated Temperature Change (top panel) and Percent Precipitation Change (bottom panel) in the Pacific Northwest from Twentieth and Twenty-first Century Global Climate Model Simulations (*Sources:* Mote and Salathé 2009, 2010).



The black curve for each panel is the weighted average of all models during the twentieth century. The colored curves are the weighted average of all models in that emissions scenario ("low" or B1, and "medium" or A1B) for the twenty-first century. The colored areas indicate the range (5th to 95th percentile) for each year in the twenty-first century. All changes are relative to 1970-1999 averages.

The Climate Impacts Group also performed projections using two regional climate models, versus ensembles of global climate models as described above (Salathé et al. 2010). Regional climate models provide the advantage of accounting for local geographic features and their effect on regional climate patterns, such as the strong influence of the Cascade Mountain Range. The results of these models confirm the warming increases described above, with variations—both slightly higher and slightly lower, depending on the emission scenario.

Projected changes in mean annual precipitation are less clear (see Figure 7). The projected trends are very small relative to the interannual variability in precipitation. Seasonally, precipitation is projected by Mote and Salathé (2009, 2010) to decrease in the summer and increase in the autumn and winter by most climate models, although the average shifts are small. However, even small changes in seasonal precipitation could have impacts on streamflow flooding, summer water demand, drought stress, and forest fire frequency. Salathé et al. (2010) project wetter autumns and drier or stable summers. But the regional models vary whether winter and spring seasons will turn wetter or drier.

In addition to changes in the amount of precipitation, a major concern in the Pacific Northwest is the change in the form of winter precipitation expected due to warmer temperatures (Knowles et al., 2006; Hamlet and Lettenmaier, 2007). Hamlet and Lettenmaier (2007) modeled changes in the current and future peak snowpack versus October-to-March precipitation for watersheds in the Columbia Basin. Generally, a large shift is projected in the form of winter precipitation from snow to rain, especially in lower elevation basins. As these changes occur, there will be likely be a tendency for higher winter flows, an increased risk of flooding, earlier snowmelt and runoff peaks, and lower summer streamflows.

Casola et al. (2009) found similar results when evaluating the impact of global warming upon Pacific Northwest snowpack using the Cascades portion of the Puget Sound drainage basin as an example. These researchers evaluated four analytical and modeling methods to determine the temperature sensitivity of snowpack. Results project a 20% reduction in snowpack (mean April 1 snow water equivalent) for each degree Celsius (1.8°F) of warming in the absence of indirect effects, and a 16% reduction in snowpack taking into account a projected warming-induced increase in precipitation. A regional modeling study in the McKenzie River Basin, Oregon, projects a higher rate with a 2°C (3.6°F) increase in temperature shifting peak snowpack 12 days earlier and decreasing basin-wide volumetric snow water storage by 56% (Sproles et al. 2013).

Considering projected warming scenarios (as described, above, Mote and Salathé 2009, 2010), the snowpack decrease amount using the analysis by Casola et al. (2009) is shown in Table 3.

Table 3: Projected Decrease in Snowpack

Average annual temperature projected increase (relative to the 1970-1999 average temperature)	**Projected decrease in Snowpack** (taking into account a projected warming-induced increase in precipitation)
2.0°F by the decade of the 2020s	18% decrease in snowpack by 2020s
3.2°F by the decade of the 2040s	28% decrease in snowpack by 2020s
5.3°F by the decade of the 2080s	47% decrease in snowpack by 2020s

This loss of snowpack is especially prevalent for the most vulnerable, lower elevation snowfields (Mote et al. 2005; Casola et al. 2007; Pederson et al. 2013; Sproles et al. 2013). Spring snowpack is a good indicator for summertime flows in many watersheds, and these snowpack loss projections therefore foretell strong negative impacts to the region's overall water resources. (Rain-dominated watersheds and those with high amounts of groundwater base flow are less sensitive (Safeeq et al. 2013)). In many watersheds in the Pacific Northwest, snowfields act as a reservoir that collects freshwater during the wetter winter months and releases this water during the drier summer months, effectively distributing water more equitably across the seasons. Loss of snowpack would disrupt this cycle, vastly altering streams whose hydrologies are largely determined by snowpack runoff and/or groundwater input.

Research on the 200 long-term (85–127 years of record) stream gages in the coterminous United States with little or no regulation or urban development find no strong statistical evidence for flood magnitudes increasing (Hirsch and Ryberg 2012).

However, globally evidence is beginning to emerge that for some types of events, notably heatwaves and precipitation extremes, increases in frequency and intensity are linked to climate change (IPCC 2011; Coumo and Rahmstorf 2012). For example, Arctic amplification– the observed enhanced warming in high northern latitudes relative to the northern hemisphere – are found to cause weather patterns in mid-latitudes to be more persistent, which may lead to an increased probability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves (Francis and Vavrus 2012).

Dominguez et al. (2012) project the intensity of future extreme winter precipitation will increase for the western United States by an area-averaged increase of 12.6% in 20-year return period (or *20-year rainfall* *events*-- a return period is an estimate of the length of time between rainfall events of a given magnitude) and a 14.4% increase in 50-year return period daily precipitation (or *50-year rainfall events*) for the period 2038-2070 when compared to the 1968-1999 historical period.

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